台灣農業研究 (J. Taiwan Agric. Res.) 74(2):141–150 (2025)
https://doi.org/10.6156/JTAR.202506_74(2).0004 **專題論述**

探討植物揮發性有機化合物的生物性功能

何佳勳[1,*] 楊滿霞[2] 蕭巧玲[2] 侯雅玲[1]

摘要

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植物釋放的揮發性有機化合物 (plant volatile organic compounds; pVOCs) 在生態體系中具有不同的生物性功能，如啟動植物防禦機制、植物間訊號傳遞、協助授粉與種子傳播、促進作物生長與適應環境逆境及提高農產品品質等。當植物遭受植食性害蟲攻擊時，會誘導釋放特殊的揮發性物質 (herbivore-induced plant volatiles; HIPVs)，吸引害蟲的天敵並啟動鄰近植物的防禦反應。此外，pVOCs 還可透過植物間訊號傳遞機制，提升鄰近植株對逆境的抵抗能力。pVOCs 的生合成來自多種生化途徑，且可分成四大類包含萜類化合物 (terpenoids)、苯丙烷類/苯類 (phenylpropanoids/benzenoids) 化合物、脂肪酸 (fatty acid) 及胺基酸 (amino acid) 衍生物。另一方面，環境因子會影響 pVOCs 的釋放量、成分含量及化學組成，其中又以溫度為關鍵因素。pVOCs 可作為生物防治與有機農業應用的潛在工具，惟其易揮發性、高生物降解性、環境干擾穩定性及生產成本高等問題，導致在農業上的應用仍受限制。若要擴大 pVOCs 的應用，仍需進一步研究與技術優化，以期能克服限制並取代傳統農藥，進而提升農業永續性。

關鍵詞：揮發性有機化合物、生物性功能、萜類化合物、生合成、溫度。

前言

植物所釋放的揮發性有機化合物 (plant volatile organic compounds; pVOCs) 在生態體系中扮演重要的訊息傳遞角色，其會吸引授粉媒介昆蟲協助花粉傳播、果實釋放香氣吸引動物協助種子散布以及植物地上部與地下部所釋放的特殊氣味，可防禦植食性動物 (herbivore) 與病原體等 (Raguso 2008; Unsicker *et al*. 2009; Ali *et al*. 2012; Hiltpold & Turlings 2012; Dudareva *et al*. 2013)。此外，pVOCs 還可保護植物避免遭受生物性 (biotic) 與非生物性 (abiotic) 逆境的損害，尤其當植物面對植食性害蟲攻擊時，則會誘導植物釋放揮發性物質 (herbivore-induced plant volatiles; HIPVs) 以吸引植食性害蟲的天敵，並引發鄰近植物的防禦反應，藉此降低植物的損害 (James & Grasswitz 2005; Ali *et al*. 2012)。另一方面，當植物遭受機械性損傷時也會短時間誘發植物釋放簡單的 pVOCs (Giorgi *et al*. 2015)。已知 pVOCs 對植物的防禦作用與授粉繁殖屬於物種特異性，主要取決於植物的遺傳特性，一般植物釋放 pVOCs 的組織器官，主要有來自開花植物的花與營養組織、針葉樹的葉子與莖，以及草本植物 (如薄荷與羅勒) 的葉片等，均會釋放出揮發性氣體 (McConkey *et al*. 2000; Knudsen *et al*. 2006; Vassão *et al*. 2006)，且不同器官在面對相同的生物性與非生物性逆境所釋放的 pVOCs 反應也不盡相同。本文旨在綜整植物揮發性有機化合物於生物性功能上的研究進展，探討其防禦機制、訊號傳遞、生合成途徑及應用潛力，並評估其在永續農業中作為生物防治資材或有機農業應用之潛力與限制，以期作為後續研究與應用技術開發之參考依據。

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* 通訊作者：chia0423@tari.gov.tw
[1] 農業部農業試驗所作物組助理研究員。臺灣 臺中市。
[2] 農業部農業試驗所作物組副研究員。臺灣 臺中市。

植物揮發性成分的生物性功能

植物防禦機制 (plant defense mechanisms)

植物所釋放的 pVOCs 可作為植食性動物篩選寄主植物的重要訊息，其主要貯存在特異化組織，如樹脂管或腺毛 (Mita *et al*. 2002)，且 pVOCs 也具有防禦機制功能，可降低植食性動物的攝食活力，並能抑制病原菌的蛋白酶活性 (Baier *et al*. 2002; Niinemets *et al*. 2013; Brilli *et al*. 2019)。植物防禦機制可分為直接與間接 2 種，其中直接防禦 (direct defense) 即植物可釋放毒性或驅避性的 pVOCs 以抑制害蟲或病原體；而間接防禦 (indirect defense) 則是植物遭受攻擊時會釋放 pVOCs 以吸引植食性害蟲的天敵 (Gols 2014)。Neri *et al*. (2007) 報告指出檸檬醛 (citral)、香芹酚 (carvacrol) 及反式-2-己烯醛 (*trans*-2-hexenal) 能有效阻礙核果褐腐病菌 (*Monilinia laxa*) 體外生長與孢子萌發。Morse *et al*. (2012) 研究指出栽培在溫室中的番茄 (*Lycopersicon esculentum* Mill) 花朵會釋放 β-phellandrene、2-carene、α-pinene 及 p-cymene 等 4 種單萜類揮發物，這些 pVOCs 可能具備毒性或驅避作用，導致熊蜂 (*Bombus impatiens* Cresson) 對其釋放量較高的花朵產生排斥反應。Marques *et al*. (2014) 研究顯示柑橘 (*Citrus sinensis* var. Valência) 花朵中所產生的芳樟醇 (linalool) 對炭疽病菌 (*Colletotrichum acutatum*) 具有明顯的體外抑制作用，當芳樟醇濃度達 1,000 mg mL^{-1} 時，則能完全抑制菌絲生長。此外，α-pinene、limonene 及 3-carene 等成分也具有抗真菌與抑制害蟲及線蟲等活性 (Hollingsworth 2005; Xu *et al*. 2014; Hwang *et al*. 2021)，綜合上述研究均屬植物直接防禦機制。Cheng *et al*. (2007) 利用轉基因水稻大量表達 OsTPS3 以產生較多的 (E)-β-caryophyllene，此揮發性成分可吸引寄生蜂 (*Anagrus nilaparvatae*) 保護水稻植株免受植食性昆蟲的侵害，進而提升水稻地上部的間接防禦能力。

植物間訊號傳遞 (plant-plant communication)

pVOCs 可作為植物與植物之間內部及外部的訊息傳遞物質，當植物遭受威脅時會釋放 pVOCs 作為訊息傳導以誘導系統性反應，使周圍植物提前啟動防禦機制，進而提升鄰近植物對抗逆境的抵抗力 (Heil & Bueno 2007; Ninkovic *et al*. 2021)，其中異戊二烯 (isoprene)、甲醇 (methanol) 及植物激素乙烯 (ethylene) 等具有高度揮發性，其訊息傳遞僅限於較短距離的植物相互作用，而萜烯 (terpene)、茉莉酸甲酯 (methyl jasmonate; MeJA)、甲基水楊酸 (Methyl Salicylate; MeSA) 或綠葉揮發物 (green-leaf volatiles) 係屬揮發性較低，能夠作為長距離訊號傳遞 (War *et al*. 2011)。Zhao *et al*. (2020) 研究顯示茶樹在寒害逆境下會釋放橙花叔醇 (nerolidol)、香葉醇 (geraniol)、芳樟醇 (linalool) 及 MeSA，這些 pVOCs 可透過 C-repeat-binding factor dependent pathway 進行訊號傳遞，進而誘導鄰近茶樹的抗寒能力。

吸引授粉者與種子傳播者 (pollination & seed dispersal)

開花植物可透過花朵釋放多樣化且高劑量的 pVOCs 吸引蜜蜂、蝴蝶等授粉傳播者，以確保植物能有效繁殖，其藉由花朵內組織特異性與發育調控所產生的氣味，以提供有關著陸與食物機會的精細空間資訊作為授粉傳播者長、短距離的引誘劑 (Raguso 2008; Dudareva *et al*. 2013)。不同的生殖器官 (如花瓣、萼片、花粉及花蜜等) 所釋放的 pVOCs 也有所差異，此種特性與優先吸引的昆蟲或化學防禦有關 (Farré-Armengol *et al*. 2013)。Byers *et al*. (2014) 報告顯示 *Mimulus lewisii* 花朵所釋放的 pVOCs 為檸檬烯 (limonene)、月桂烯 (myrcene) 及羅勒烯 (ocimene)，其中又以檸檬烯為吸引大黃蜂 (*Bombus vosnesenskii*) 授粉最為關鍵。另一方面，果實成熟後也會釋放 pVOCs 以吸引動物攝食，進而促進種子傳播並有助於生態系內植物族群的空間移動 (Dudareva *et al*. 2013)。Youngsteadt *et al*. (2008) 研究指出附生植物 (*Peperomia macrostachyam*) 種子所釋放的 pVOCs 混合物會吸引亞馬遜雨林的巨山蟻 (*Camponotus femoratus*) 對種子的收集行為，進而促進種子傳播。

促進作物生長與適應環境逆境

pVOCs 可能具有植物生長調節作用，藉由

與其他代謝物與植物荷爾蒙協同作用，共同參與調節植物老化 (senescence) 過程，且 pVOCs 也可產生植物間的相剋作用 (allelopathy) 抑制鄰近雜草種子的發芽與根部生長，進而提升自身在有限資源下的競爭力與適應能力 (Brilli *et al*. 2019)。Dani *et al*. (2016) 研究顯示異戊二烯類 (isoprenoids)、類胡蘿蔔素 (carotenoids) 與細胞分裂素 (cytokinins) 在成熟葉片中共同維持光合系統 (photosystems) 結構與功能的穩定，有效降低活性氧類 (reactive oxygen species; ROS) 所造成的氧化損傷，進而延長葉片功能壽命，提升植物逆境適應力與作物整體生產力。Gfeller *et al*. (2019) 研究指出斑矢車菊 (*Centaurea stoebe*) 根部所釋放的 pVOCs 含有豐富的倍半萜烯 (sesquiterpene)，以 (E)-β-caryophyllene 與 daucadiene 為主要成分，其會影響鄰近植物的種子發芽與生長，進而改變植物群落的結構分佈。Srikanth *et al*. (2024) 報告顯示植物釋放的異戊二烯 (isoprene) 具有清除逆境所產生之 ROS 的能力，並能抑制一氧化氮 (nitric oxide)、過氧化氫 (hydrogen peroxide)、臭氧 (ozone) 及單線態氧 (singlet oxygen) 的累積，進而減少細胞氧化損傷，提升植物耐高溫與抗氧化逆境的能力。綜合文獻研究顯示，pVOCs 具有穩定細胞膜結構與清除 ROS 的能力，有效減緩因環境逆境所造成的細胞損傷，其主要透過降低膜脂質過氧化程度、維持葉綠體細胞膜功能與抑制 ROS 累積，進而提升植物對逆境的適應能力 (Loreto & Velikova 2001; Velikova *et al*. 2011; Brilli *et al*. 2019)。

提高農產品品質 (food quality improvement)

pVOCs 為農產品的香氣、風味及品質之指標之一，如檸檬烯 (limonene) 為柑橘類水果的主要芳香成分 (Viuda-Martos *et al*. 2009)；而己烯醛 (hexenal) 是櫻桃番茄 (*Lycopersicum esculentum*) 的主要香氣成分 (Selli *et al*. 2014)；咖啡豆烘焙過程中所產生的 pVOCs 則為決定咖啡品質的重要因素，其中又以含硫化合物 (sulfur-containing compounds) 與吡嗪類 (pyrazines) 被認為是影響咖啡風味的成分 (Sunarharum *et al*. 2014)。此外，揮發性成分含有重要風味，也有助於人體健康等益處 (Ayseli & Ayseli 2016)。Park *et al*. (2012) 研究指出芳樟醇與其降解產物 α-松油醇 (α-terpineol) 對牙周病菌 (periodontopathic) 與致齲菌 (cariogenic bacteria) 具有強效的抗菌活性。Miyazawa *et al*. (2016) 研究顯示紅鳳菜精油可抑制乙醯膽鹼酯酶 (acetylcholinesterase; AChE) 的活性，且倍半萜類抑制 AChE 的活性高於單萜類化合物。綜整文獻有關植物揮發性有機化合物的生物性功能，詳見表 1。

植物揮發性成分的生合成

由於 pVOCs 具備低分子量、親脂性以及在常溫常壓下具高蒸氣壓等特性，使其得以穿透細胞膜並釋放至外界環境 (Pichersky *et al*. 2006)。pVOCs 的生合成主要依賴碳、氮與硫元素，以及初級代謝所提供的能量來源，而其生合成來源可分為幾類，包含萜類化合物 (terpenoids)、苯丙烷類/苯類 (phenylpropanoids/benzenoids) 化合物、脂肪酸 (fatty acid) 及胺基酸 (amino acid) 衍生物 (Dudareva *et al*. 2006, 2013)，有關植物揮發性成分之簡易生合成途徑，如圖 1。萜類化合物 (terpenoids) 是植物次級代謝物中數量最多的一類，如植物精油乃存在於植物體內的天然有機物質，是由多種揮發性成分所構成的混合物，其主要成分即為各類萜類化合物，如異戊二烯類 (isoprenoids, C_5)、單萜類 (monoterpenoids, C_{10}) 及倍半萜類 (sesquiterpenoids, C_{15}) 等，這些萜類化合物主要由碳水化合物透過糖解作用生成丙酮酸 (pyruvate)，再經由細胞質的甲羥戊酸 (mevalonic acid; MVA) 與質體的甲基赤蘚糖醇磷酸鹽 (methylerythritol phosphate; MEP) 途徑促成之生合成，其中 MVA 途徑會產生揮發性的倍半萜類 (C_{15})，而 MEP 途徑則會產生半萜類 (hemiterpenes, C_5)、單萜類 (C_{10}) 及二萜類 (diterpenes, C_{20}) 的前驅物 (Holopainen & Gershenzon 2010; Dudareva *et al*. 2013)。

第二大類 pVOCs 為苯丙烷類與苯類化合物 (phenylpropanoids/benzenoids)，其生合成主要源自芳香族胺基酸的苯丙胺酸 (phenylalanine; Phe)，並經由質體中的莽草酸/苯丙胺

表 1. 綜整文獻有關植物揮發性有機化合物的生物性功能。

Table 1. Comprehensive references regarding the biological functions of plant volatile organic compounds (pVOCs).

Plant	pVOC compounds	Biological functions	References
Cherry tomato; stone fruits	*trans*-2-hexenal (*Z*)-3-hexenal (*E*)-2-hexenal	(*Z*)-3-hexenal and (*E*)-2-hexenal were the primary aroma-active compounds in cherry tomatoes. *Trans*-2-hexenal exhibits the strongest antifungal activity against *Monilinia laxa*.	Neri *et al*. 2007; Selli *et al*. 2014
Citrus fruits; tea	linalool	It exhibits potent antifungal activity, effectively preventing citrus postbloom fruit drop caused by *Colletotrichum acutatum*, and functions as an inducible volatile that triggers interplant communication.	Marques *et al*. 2014; Zhao *et al*. 2020
Citrus fruits; *Mimulus lewisii*	limonene	It is the primary aromatic component of citrus fruits and plays a role in controlling mealybugs and scale insects, while also acting as a driver of pollinator-based speciation.	Hollingsworth 2005; Viuda-Martos *et al*. 2009; Byers *et al*. 2014
Pines; tomato	2-carene 3-carene	2-Carene has repellent and toxic effects on insect species and constitutes the major component of the tomato floral scent. 3-Carene exhibits strong antifungal activity and weak nematicidal activity in pine.	Morse *et al*. 2012; Hwang *et al*. 2021
Pines; tomato	α-pinene	It exhibits repellent and toxic effects on insect species and inhibits the feeding activity of bark beetles.	Morse *et al*. 2012; Xu *et al*. 2014
Rice; spotted knapweed	(*E*)-β-caryophyllene	It plays a role in indirect defense by attracting parasitoid wasps and may further support the germination and growth of neighboring plants.	Cheng *et al*. 2007; Gfeller *et al*. 2019
Stone fruits	citral	It moderately inhibits both conidial germination and mycelial growth of *Monilinia laxa*.	Neri *et al*. 2007
Stone fruits	carvacrol	It exhibits inhibitory effects on the mycelial growth of *Monilinia laxa*.	Neri *et al*. 2007
Tea	nerolidol	Acts as an inducible volatile signaling neighboring plants to respond to cold stress.	Zhao *et al*. 2020
Tea	geraniol	Acts as an inducible volatile signaling neighboring plants to respond to cold stress.	Zhao *et al*. 2020
Tomato	p-cymene	It exhibits repellent and toxic effects on insect species.	Morse *et al*. 2012
Tomato	β-phellandrene	It has repellent and toxic effects on insect species and constitutes the major component of the tomato floral scent.	Morse *et al*. 2012

酸 (shikimate/phenylalanine) 途徑所產生，此途徑起始於赤鮮糖-4-磷酸 (erythrose 4-phosphate) 與磷酸烯醇丙酮酸 (phosphoenolpyruvate; PEP) 之縮合，形成莽草酸 (shikimate) 中間產物，進一步經由 3-dehydroshikimic acid 與 chorismate 等一系列酵素促進反應，最終生成苯丙胺酸 (Phe)。Phe 經由苯丙胺酸脫氨裂解酶 (phenylalanine ammonia lyase; PAL) 作用，轉化為反式肉桂酸 (trans-cinnamic acid)，進一步合成羥基肉桂酸類 (hydroxycinnamic acids)，並經由甲基化 (methylation) 與羥基化 (hydroxylation) 修飾後，產生多種具揮發性的羥基肉桂酸衍生物、醛類及醇類等芳香化合物 (Dudareva *et al*. 2013; Niinemets *et al*. 2013)。

第三大類 pVOCs 為脂肪酸衍生物 (fatty acid derivatives)，如 1-己醛 (1-hexanal)、順式-3-己烯醇 (*cis*-3-hexenol)、壬醛 (nonanal) 及 MeJA 等。此類揮發物主要由乙醯輔酶 A (acetyl-CoA) 為起始物，進行脂肪酸生合成，產生 C_{18} 不飽和脂肪酸，如亞麻油酸 (linoleic acid) 與次亞麻油酸 (linolenic acid)，這些不飽和脂肪酸為脂肪酸衍生 pVOCs 的前驅物，經由氧化進入脂氧合酶

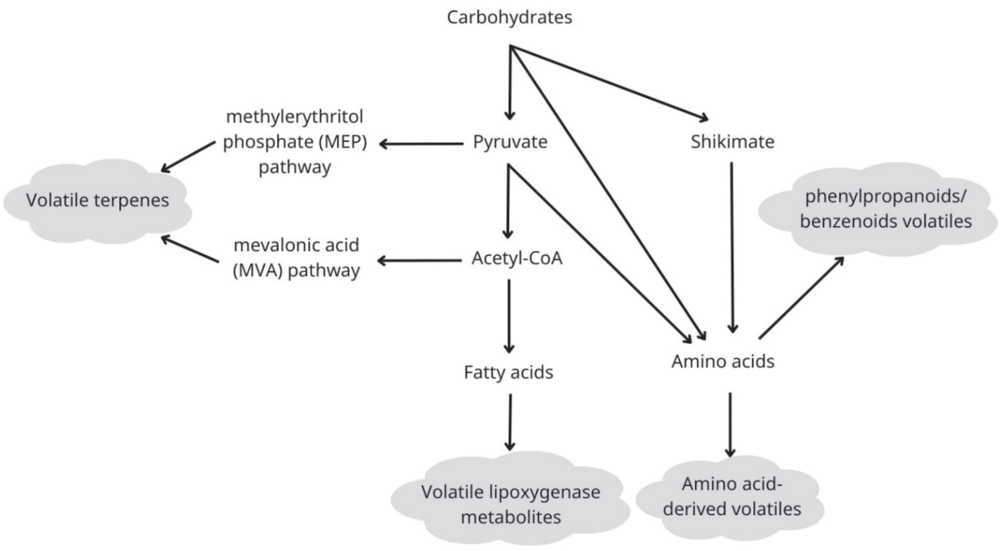

圖 1. 植物揮發性成分之簡易生合成途徑。
Fig. 1. Simplified biosynthetic pathways of plant volatile organic compounds (pVOCs).

(lipoxygenase; LOX) 途徑產生 9-hydroperoxy 與 13-hydroperoxy 中間產物，再進一步由過氧化物水解酶 (hydroperoxide lyases; HPLs) 與醇脫氫酶 (alcohol dehydrogenases; ADHs) 等酵素的作用下，轉化為多種具有揮發性的醛類與醇類化合物，此類 pVOCs 通常被稱為綠葉揮發物 (green leaf volatiles; GLVs)，其生合成多發生於植物綠色器官受損時，不僅參與植物防禦反應，也是許多蔬果呈現新鮮綠色氣味的主要來源 (Feussner & Wasternack 2002; Bruinsma *et al*. 2009)。

第四大類 pVOCs 為胺基酸衍生物 (amino acid derivatives)，包含醛、醇、酯、酸以及含氮與含硫的揮發物均來自胺基酸，如丙胺酸 (alanine)、擷胺酸 (valine)、白胺酸 (leucine)、異白胺酸 (isoleucine) 及甲硫胺酸 (methionine) 等胺基酸或其生物合成中間產物，當胺基酸經脫氨基 (deamination) 或轉氨基 (transamination) 後生成 α-酮酸 (α-keto acid)，再經由脫羧 (decarboxylation)、還原 (reductions)、氧化 (oxidations) 及酯化 (esterification) 等作用產生醛、酸、醇、酯，此類 pVOCs 主要為花香與果香中的揮發性化合物 (Dudareva *et al*. 2006; Knudsen *et al*. 2006)。

溫度對植物揮發性成分的影響

植物揮發性氣體的組成與植物種類 (species)、器官 (organs)、發育階段 (developmental stages) 及環境條件 (environmental conditions) 有關，在果實特定的發育階段與植物不同的組織部位 (如葉、根及花) 等，均可檢測到揮發性化合物的產生與釋放 (Possell & Loreto 2013; Ren *et al*. 2014; Chiu *et al*. 2017)。另一方面，環境因子對揮發性成分的影響，包含光照強度、二氧化碳濃度、溫度、相對濕度及營養等 (Staudt & Bertin 1998; Gouinguené & Turlings 2002; Ren *et al*. 2014)，而溫度對 pVOCs 的合成與釋放乃是關鍵環境因子之一 (Guenther *et al*. 2012; Grote *et al*. 2013; Copolovici & Niinemets 2016)。Harley (2013) 研究顯示，溫度會決定植體中 pVOCs 的氣相-液相分布情形，即當溫度升高時，揮發性化合物會轉化成氣體並從植體中釋放出去。此外，葉面特徵、空氣溫度、葉面溫度以及揮發物的物理化學性質是決定葉面 pVOCs 沉積與再釋放的重要因素 (Schaub *et al*. 2010; Niinemets *et al*. 2014)。Gouinguené & Turlings (2002) 研究顯示玉米 (*Zea mays*) 植株的氣味主要由萜烯

(terpenoids) 與吲哚 (indoles) 所組成，不同環境因子會影響揮發性氣體的釋放量，而在 22 與 27℃會有最高的釋放量，且溫度亦會改變氣味成分的含量，研究發現在 37℃高溫下 β-caryophyllene 比例最高，而 geranyl acetate 含量則在 22℃下較多。Chang *et al*. (2005) 研究指出羅勒 (*Ocimum basilicum* L.) 最適生長溫度為 25℃，在此溫度環境下會有最佳的生長參數與揮發性化合物含量；此外，溫度亦會影響揮發性成分的組成，如在 25℃下會使 eugenol 與 *cis*-ocimene 含量增加，而 15℃下則會累積 camphor 與 *trans*-β-farnesene 的含量。Prodhan *et al*. (2017) 報告指出除了基因型會影響香米氣味之外，揮發性化合物的組成亦決定香米的香氣狀態，且環境溫度也會影響揮發性成分的組成與含量變化進而改變香氣表現，其發現在 25℃下可獲得最佳的香氣官能品評。Ho *et al*. (2021) 研究顯示不同的栽培溫度會影響紅鳳菜 (*Gynura bicolor* DC) 葉片的單萜類 (monoterpenoids) 與倍半萜類 (sesquiterpenoids) 組成含量，其中總單萜類含量在 20 與 25℃最高，而總倍半萜類含量則在 30 與 35℃最佳，且 α-pinene 與 α-humulene 的相對含量在 20℃最高，而 copaene 則在 35℃最好。綜合文獻研究可知，溫度是影響 pVOCs 釋放量、成分含量及化學組成的關鍵因素。

結語

綜合上述研究顯示，pVOCs 在農業中具有多種潛在應用性，如天敵誘導與害蟲防治、增強作物抗病能力、促進作物生長及提高品質等，且 pVOCs 還可作為天然殺蟲劑或驅避劑等友善環境的農藥替代品，以減少田間化學農藥使用。然而，pVOCs 具有易揮發與高生物降解性，且易受環境因素影響，導致 pVOCs 的持續性與穩定性不足，再加上 pVOCs 的作用範圍有限，難以在田間栽培中發揮穩定效果。另一方面，pVOCs 在應用時可能會影響非目標生物 (如授粉昆蟲)，因此需進一步評估生態安全性，且萃取或合成 pVOCs 成本較高，目前商業應用仍受到限制。目前 pVOCs 可作為生物防治與有機農業應用的輔助策略，但尚未能完全替代傳統農藥，若要擴大 pVOCs 的應用，仍需克服上述限制條件且進一步研究與技術優化。

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Exploring the Biological Functions of Plant Volatile Organic Compounds

Chia-Hsun Ho[1,*], Man-Hsia Yang[2], Chiao-Ling Hsiao[2], and Ya-Ling Hou[1]

Abstract

Ho, C. H., M. H. Yang, C. L. Hsiao, and Y. L. Hou. 2025. Exploring the biological functions of plant volatile organic compounds. J. Taiwan Agric. Res. 74(2):141–150.

Plant volatile organic compounds (pVOCs) exhibit various biological functions in ecosystems. These include activating plant defense mechanisms, facilitating plant-to-plant signaling, aiding in pollination and seed dispersal, promoting crop growth and environmental adaptation, and enhancing agricultural product quality. When herbivorous insects attack plants, they induce plants to release specific volatile compounds, known as herbivore-induced plant volatiles (HIPVs), which attract natural enemies of pests and trigger defense responses in neighboring plants. Additionally, pVOCs involve plant-to-plant communication, enhancing the resistance of surrounding plants under stresses. The biosynthesis of pVOCs originates from multiple biochemical pathways and can be categorized into four major groups: terpenoids, phenylpropanoids/benzenoids, fatty acid derivatives, and amino acid derivatives. On the other hand, environmental factors influence the emission levels, composition, and chemical properties of pVOCs, with temperature being a key determinant. The pVOCs show significant potential as biocontrol agents for organic agriculture. However, their high volatility, rapid biodegradability, sensitivity to environmental conditions, and high production costs pose challenges to their widespread agricultural application. Further research and technical improvements are needed to overcome limitations before pVOCs can effectively replace traditional pesticides in sustainable agriculture.

Key words: Volatile organic compounds, Biological functions, Terpenoids, Biosynthesis, Temperature.

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[*] Corresponding author, e-mail: chia0423@tari.gov.tw
[1] Assistant Research Fellows, Crop Science Division, Taiwan Agricultural Research Institute, Taichung City, Taiwan, ROC.
[2] Associate Research Fellows, Crop Science Division, Taiwan Agricultural Research Institute, Taichung City, Taiwan, ROC.